Neutrino-Induced Giant Air Showers in Large Extra Dimension Models

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Abstract: In models based on large extra dimensions where massive spin 2 exchange can dominate at high energies, the neutrino-proton cross section can rise to typical hadronic values at energies above 10^{20} eV. The neutrino then becomes a candidate for the primary that initiates the highest energy cosmic ray showers. We investigate characteristics of neutrino-induced showers compared to proton-induced showers. The comparison includes study of starting depth, profile with depth, lateral particle distribution at ground and muon lateral distribution at ground level. We find that for cross sections above 20 mb there are regions of parameter space where the two types of showers are essentially indistinguishable. We conclude that the neutrino candidate hypothesis cannot be ruled out on the basis of shower characteristics.

1 Introduction

Many ultra high energy (UHE) cosmic ray air showers with energies in excess of 5×10^{19} eV have been observed in the past few decades [1]. The nature and origin of the primary particles is not understood [1, 2, 3]. The puzzle is that the sources have to be within the GZK limit of approximately 50 Mpc if these particles are protons or nuclei [4, 5]. However there are not enough powerful astrophysical sources within this distance to explain the events.

Among known particles, only neutrinos travel larger distances than protons in intergalactic space. This leaves neutrinos as the only established candidates that can travel the distances greater than 100 Mpc from known UHE sources. The GZK bound of 50 Mpc is not applicable to them. Yet neutrino interactions with matter are too weak in the Standard Model of particle physics to generate the observed air showers. Hence these events

seem to demand a revision of our current understanding of nature. Either the determination of the number of sources of such ultrahigh energy particles in our astrophysical neighborhood is grossly low[1], or these observations are a signal of new physics.

Many speculative ideas have been proposed to explain the events above $10^{19} - 10^{20} eV$, including topological defects such as cosmic strings [6, 7] and associated decays of heavy, relic particles [8, 9], existence of neutral, stable, strongly interacting particles, such as a light gluino [10, 11, 12] or a monopole bound state [13, 14], and violation of Lorentz invariance [15, 16]. Much of this work requires that the primary particle responsible for generating these air showers is an exotic new particle which does not exist within the Standard Model.

In a recent paper [17] we argued that the data is consistent with the general features of massive spin-2 exchange. Models where effects of gravity can be strong just above the weak scale [18] supply a natural and attractive framework. The interaction cross section of neutrinos with matter is greatly enhanced with massive spin-2 exchange at UHE and may reach values close to the hadronic cross sections. In the low scale gravity models, the cross section enhancement arises from t-channel exchange of the tower of gravitons. Our estimates of the neutrino-proton cross section at the highest energies relevant for these events are of the order of one to a few hundred millibarns. The highest energy cosmic ray events may therefore be initiated by neutrinos[2][17, 19].

A generic, robust prediction of massive spin-2 exchange, known for many decades, is that the total cross section should grow with a power of energy, typically $\sigma_{tot} \sim s^2$. The property of power law growth with a power exceeding 1 (the result of 4-Fermi *spin-1* exchange) is quite hard to evade and can be traced to dimensional analysis. We consider large cross sections at UHE to be characteristic of extra-dimension, low scale gravity models. Interaction of UHE neutrinos is a quite natural domain to seek the new effects of low scale gravity models: the very weakness of the Standard Model neutrino coupling minimizes this background, while the regime of of highest possible energy maximizes the effects of graviton-KK mode exchange.

[1]For example if magnetic fields outside the galaxy have been underestimated, "line of sight" and "photon travel time" requirements on protons and nuclei can be relaxed and new source possibilities considered [2]

[2]Correlation between the positions of compact radio quasars and the track directions of UHE > 100 EeV cosmic rays has been studied by several groups [20, 21, 22].

The theory of low-scale gravity models is only partly developed, and questions of unitarity complicate the interpretation of perturbation theory [23]. One can choose models of the cross section which are further from the calculations of perturbation theory in the sense that they grow at a slower rate with energy than s^2 (The perturbative, parton level cross section rises as $\hat{s}^3$) [24, 25, 27], or which operate by a separate (s-channel) mechanism [28]. Indeed it is possible to restrict models of low-scale gravity to the extent that nothing observable is predicted at the energies in question. For example, the astrophysical bound on the scale parameter M for the n=2 case guarantees that the consequences of this model are unobservable [24],[25].

There has been some confusion on this point. Let us compare the model we use here, taken from our previous cross section calculations [17], with subsequent work [25]. The latter reports the result of assuming that a finite brane tension introduces an exponential damping of higher KK modes, providing an alternative cutoff mechanism [26]. Like our calculation, when $\sqrt{s} \geq M$, the cross section in [25] rises approximately quadratically with neutrino energy (See Fig. 1 in [25], where $\sigma_{\nu N}$ rises by two orders of magnitude for every order of magnitude rise in E_ν). Unlike ours, the calculation there assumes n=2 only, for which SN1987a analysis makes the restriction $M \geq$ 30-70 TeV [34].[3] If $n \geq 3$ were considered, the scale could be lowered to the 2-3 TeV range and cross section values in agreement with ours would result. This is clear from the trend with mass scale in Fig. 1 in [25]. Conversely, we could suppress our cross section to their values by raising M to values of 6 TeV and above. Specifically, we find that $\beta = 1$ and $M = 6$ TeV yields $\sigma_{\nu N} = 0.3$ mb, compared to 0.1 mb at $E_\nu = 10^{20}$ TeV for $M = 6$ TeV in [25], while the choice $\beta = 2$ and $M = 6.6$ TeV or $\beta = 1$ and $M = 7.3$ TeV reproduces their 0.1 mb value. Within modest parameter variations, the results clearly agree. This is not a surprise, since the parton level amplitudes and cross sections for small t are essentially identical, and are insensitive to the value of n in the two cutoff methods [26]. The two calculations differ only in the details of the large t cutoffs, both of which produce s^2 behavior of the cross sections. The cutoff used in in [25] gives a cross section result in essential agreement with ours at a given set of E_ν and M values. Their assertion to the contrary is an unfortunate consequence of presenting the results for a lower bound $M \geq 6$, justified only for n=2, and drawing sweeping,

[3]Citing uncertainties in astrophysical parameters, [25] considers M values as low as 6 TeV.

unjustified conclusions about the general situation. With this technical issue clarified about the particular model we employ, we reiterate that our goal is to explore the broad consequences of strongly interacting UHE neutrinos.

The primary, general question that arises, defining our focus here, is the nature of *air shower development*. High-energy leptonic interactions do not have the same multiplicity or inelasticity as high energy hadronic interactions. To understand the potential relevance of neutrino interactions, one must address not only the total cross section, but also the way the interaction delivers energy into the air showers that are actually observed.

In the present paper we compare simulations of air showers generated by neutrino primaries with large cross sections to those generated by protons in the Standard Model. We ask whether there is anything about existing showers which might *rule out* neutrinos as primaries.[4] If so then the case is made that large cross sections alone are not enough to support the case for neutrinos, and speculative models of *new* particles might be indicated.

Contrary to some expectations [25], we find that neutrinos with large cross sections *can create showers that are much like proton-initiated showers* and that in some cases are indistinguishable from them [29] [30]. Two features of the low-scale gravity contribution to the neutrino-nucleon cross section come into play: first, the cross section is large enough to initiate air showers at high enough altitudes; second, its rapid s^2 dependence suppresses new effects among secondary products, which carry at most a few percent of the primary energy. Our methodology can evidently be extended to other models for hadronic size UHE neutrino cross sections provided the cross sections grow rapidly (as in spin-2 exchange). Other speculative primaries should be considered on a case-by- case basis. One cannot take the existence of one model that produces well simulated showers above 10^{20} eV to be conclusive evidence for a given hypothesis for the identity of the primary, neutrino or otherwise. The question of the mysterious primary, then, needs to be framed in view of everything that can be observed: cross sections, shower characteristics, and angular distributions and correlations, which may be informative about the charge of the primary.

[4]Alternatively one might ask whether one can "find evidence" for neutrinos as the primaries in some features of the showers. We do not pursue this, because the fluctuations of air showers and flexibility in simulation codes make it a very hard and ambiguous way to proceed.

2 Air Showers with Neutrino Primaries

The neutrino proton cross section is significantly modified at ultra high energies due to graviton exchange within low scale gravity models [18]. Within these models the Feynman rules can be found in [31]. These rules, derived for the case of a common compactification scale for all compact dimensions, are applicable only at energies smaller than the fundamental scale of quantum gravity M. We are not primarily concerned here with variations on the theory, which can raise and lower scales somewhat, [5] but we do assume that any new physics has a scale of about 1 TeV. [6] Experimental limits on the effective scale in the theory depends on the number of extra dimensions in the Universe. If the number of extra dimensions is larger than 2, and a common compactification scale is assumed, then M is constrained to be larger than about 4 TeV, 1 TeV and 0.5 TeV for n = 3, 4 and 6. [34]. Given uncertainties in the estimates, these are all acceptable for our purposes. The energies involved in the ultra high energy cosmic ray events are much larger than these scales. In order to extend our calculations beyond the scale M some modelling is required, since the calculational procedure beyond this scale within quantum gravity is unknown.

Our procedure is to make calculations with several different models. At the parton level above $\sqrt{s} \simeq M$, the cross sections rise with $\hat{s}$ either as $\hat{s}^n$, with $n = 1, 2$ or as $(\log \hat{s})^2$. A natural feature of the perturbative $\hat{s}^3$ growth of the spin-2 exchange below the scale M is that the effects of new physics lie *well below* the sensitivity of accelerator experiments below this scale. The new cross section effects rise to become comparable to the Standard Model alone at about $\sqrt{s} \simeq M$, as expected. The total cross section then rises quickly above the Standard Model above $\sqrt{s} \simeq M$. Depending on the choice of M and the model used we found that the cross sections range from 1 mb to several hundred mb at energies of the order of 10^{20} eV [17].

We developed a program that can generate air showers with a non standard neutrino primary using the AIRES and PYTHIA simulators. The steps in this Monte Carlo simulation are as follows: (1) The neutrino collides with

[5] Experimental bounds are generally restricted to the case where a common radius is assumed. This restriction is convenient, but not necessary, as remarked for example in [32].

[6] We are not considering models where gauge and matter fields propagate in the extra dimensions. Bounds that apply to such models and to the n=2, common radius model of low scale gravity are reviewed in [33], for example.

an air nucleus at an altitude which is determined by the scattering cross section. The neutrino proton cross section is calculated by using the methods explained in Ref. [17]. The neutrino-nuclei cross section can then be computed using the standard Glauber formalism [35]. (2) The neutrino typically loses less than 10% of its energy in any of these collisions, a point which has earlier been emphasized by [25]. The neutrino typically undergoes collisions with several protons in the first nucleus as well as the subsequent ones it hits. The number of hits on target nucleus of weight A is given by [36]

$$n_{\text{hits}} = \frac{A\sigma_{\nu p}}{\sigma_{\nu A}}$$

In step (3), for each of the hits we determine the outgoing particles by using PYTHIA. (4) We stack all the final state particles produced by the PYTHIA simulation except those which originate from the decays of π^0 and K^0. We inject π^0 and K^0 directly since these can be processed by AIRES. These are stacked into AIRES at each point that the neutrino proton collision occurs. This sequence is then reproduced probabilistically over the course of the shower.

Let us emphasize again that our primary interest here is the development of showers initiated by a large cross section, low inelasticity, neutral-current-like primary interaction. Models where only the neutrino-hadron interaction feels the new physics can readily be treated with our analysis. In the particular class of models that we consider, the hadronic interactions of the secondaries are, in principle, also affected. In practice, these effects are not important. The energy transfer to the hadron system is less than 10% of E_ν per collision. The multiplicity at 10^{20} is of order 100. We find that the nominal value of $0.01 \times E_\nu$ per secondary can fluctuate up to as much as $0.05 \times E_\nu$ for one or two secondaries. This still leaves the highest energy secondaries with less than $10^{19} eV$ "lab energy". Even the largest cross sections we consider are ≤ 1 mb in this energy range, much smaller than the expected values of order 100 mb for the SM hadronic cross sections. It is clear that the showers will not be significantly affected by changes of 1% in one or two particles in the shower. For this reason we do not include the KK graviton excitation corrections to the secondary hadron interactions.

In our simulations we study the quantum gravity parameter space such that the neutrino proton cross section ranges from about 10 mb to several hundred millibarns. This is a reasonable range, suggested by bounds based on experiments. There are two notable regimes:

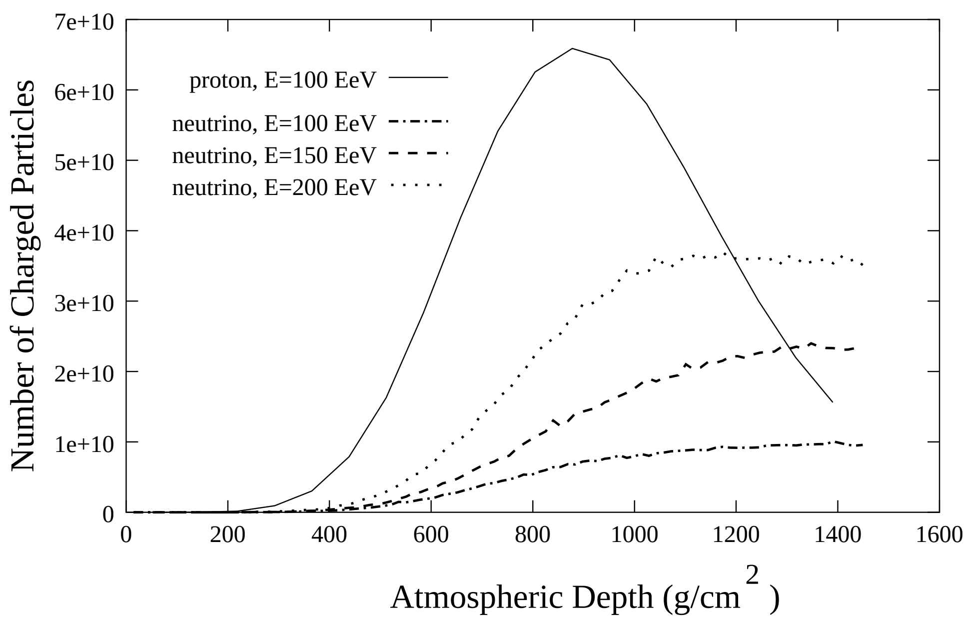

Figure 1: The longitudinal shower profiles averaged over 50 showers for the case when the neutrino proton cross section $\sigma_{\nu p}$ is less than about 20 mb at the ultra high energies of the order of 100 EeV. The longitudinal profile for neutrino induced shower profiles with primary energy E=100 EeV (dash dot curve), 150 EeV (dashed curve) and 200 EeV (dotted curve) are compared with a proton induced shower with primary energy of 100 EeV (solid curve). The $\sigma_{\nu p}$ for this case is obtained by using the linear rise model, $\hat{\sigma} \propto \hat{s}$, where $\hat{\sigma}$ and $\hat{s}$ are the parton level cross section and center of mass energy respectively. The $\sigma_{\nu p}$ values are 9.4 mb, 15.3 mb and 21.5 mb for primary energy E=100, 150 and 200 EeV respectively.

*If we lower the cross section below about 20 mb we find that the air showers generated are very different from those initiated by a proton. For instance, the showers are stretched out by 50% or more, with the location of shower maximum delayed by a similar amount[7]. This behavior is illustrated in Fig. 1, where the shower profile averaged over 50 showers for a proton primary with energy 100 EeV is compared to the profiles for a neutrino primary with linearly rising cross section and energies of 100, 150 and 200 EeV. The neutrino proton cross sections in this case are 9.4 mb, 15.3 mb and 21.5 mb for neutrino energy E=100, 150 and 200 EeV respectively. Though interesting in their own right, these cases will not be readily confused with the observed highest energy showers.

*If the cross sections are much larger than about 20 mb, then a variety of things can occur. When the neutrino - proton cross section is about the same as the proton - proton cross section, we find that the showers generated by neutrinos *may or may not* differ in detail from those generated by protons. There is always a region of parameter space where the difference in showers is too small to detect. We therefore concentrate this study on the larger cross section values attainable with the characteristic s^2 "Regge" rise[17].

Compared to a proton, the neutrino loses a small amount of energy per collision. For this reason a neutrino undergoes collisions with many air nuclei. The interaction basically occurs along a line rather than at a single point[8]. A proton shower will arise primarily from the proton's collision with a single air nucleus, since the energy loss per collision is large and the secondary showers generated by collision of the remnants of the incident proton with other air nuclei will be relatively weak. The shower-to-shower fluctuations can still be large, however, and detailed study is required.

3 Results and Discussion

We compare the structure of neutrino induced showers to proton induced showers using the "Regge model" cross section mentioned above [17]. We also show in Fig. 1 a few selected cases of showers induced by the linear-in-s cross section case to illustrate that lower cross section, deeper and more

[7]These smaller cross section values are interesting from the point of view of horizontal shower searches [37].

[8]This effect, which explains the observed spread in arrival times of particles far from the core [1], is exaggerated in neutrino induced compared to proton induced showers.

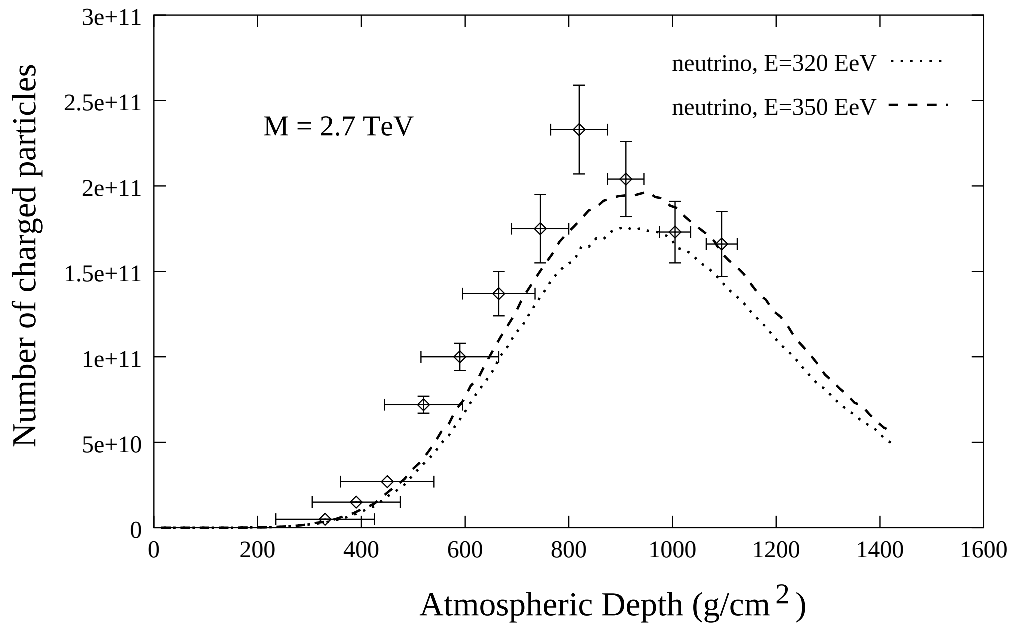

Figure 2: The longitudinal profile of showers generated by neutrino primaries compared to the Fly'e Eye data. The dotted and dashed curves show mean over 50 showers with neutrino primary energy $E = 320$ EeV and 350 EeV respectively. The quantum gravity scale $M = 2.7$ TeV is used in these simulations.

extended events are rather distinct. The choice $\beta = 1$ is sufficient for our study, and all of the plots from Fig. 2 onwards are made with this value[9]. The injection energy of the neutrino and the value of M are then chosen to create a shower to be compared with data or with a simulated proton shower of prescribed energy.

Of all the ultra high energy cosmic ray detectors, only the Fly's Eye and its offspring HiRes track longitudinal development of the showers. To start our comparison of neutrino and proton initiated showers, we show in Fig. 2 the profile, or number of charged particles vs. depth, of the highest energy cosmic ray event ever observed. The data points are the best reconstruction of the event, as analysed and presented by the Fly's Eye group [38]. The energy is quoted as 320 EeV, and we superpose the profiles averaged over 50

[9]The momentum transfer has a cutoff $1/(M^2 - \beta t)$ in this model.

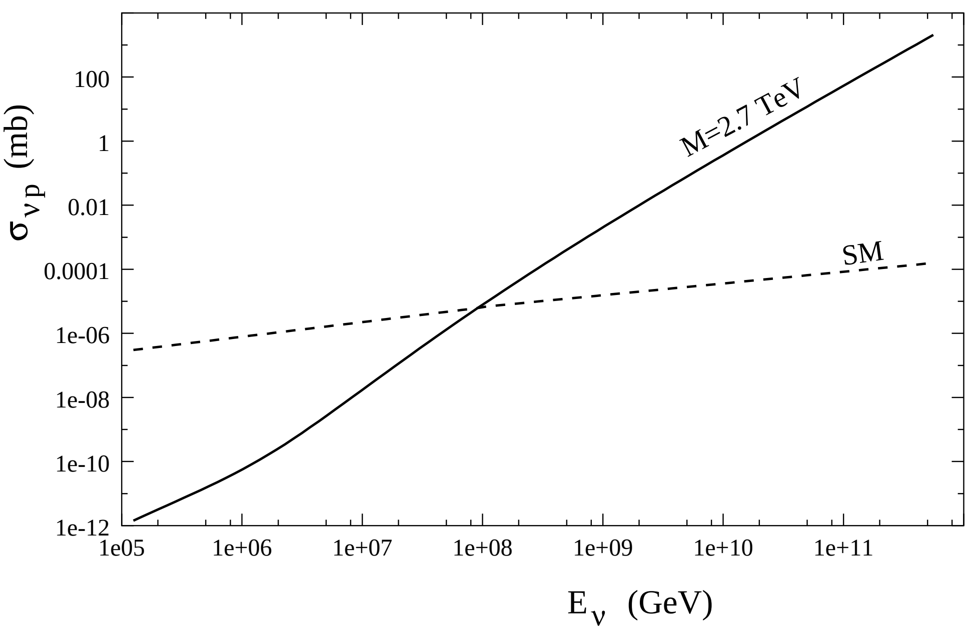

Figure 3: The neutrino-proton cross section, $\sigma_{\nu p}$, in large extra dimension models assuming s^2 growth of parton level cross section with the quantum gravity scale $M = 2.7$ TeV (solid curve) compared to the standard model result (dashed curve).

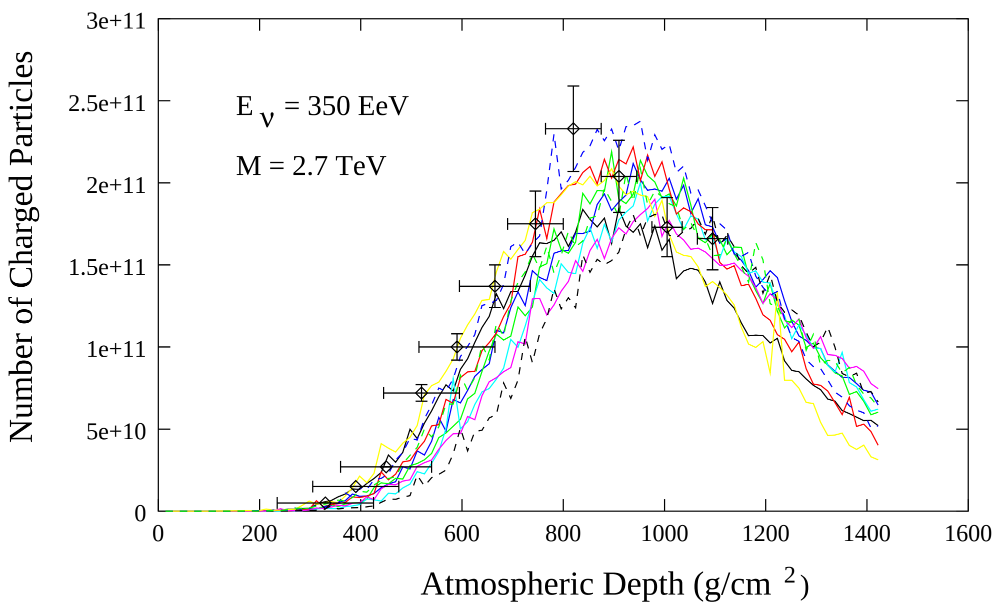

Figure 4: The longitudinal profile of 10 showers generated by neutrino primaries compared to the Fly'e Eye data. The neutrino primary has energy $E = 350$ EeV and the quantum gravity scale $M = 2.7$ TeV is used in these simulation.

simulated neutrino-induced showers for the case $M = 2.7$ TeV and energies $E_\nu = 320$ EeV and 350 EeV. The corresponding neutrino-proton cross section with the quantum gravity scale $M = 2.7$ TeV is shown in Fig. 3. As noted by Bird et al. [38], the best fit value of the depth of the shower maximum is consistent with the primary being a proton, midsize nucleus, heavy nucleus or even a gamma ray. Could it have been a neutrino? In Fig. 4 we show the same data and the profiles of 10 simulated individual neutrino showers with $M = 2.7$ TeV and $E_\nu = 350$ EeV. The shower-to-shower fluctuations are vividly illustrated, with the envelope doing a good job of capturing the event. From this example, we would say a neutrino primary with a large cross section but a small energy transfer per collision like a neutral current interaction and an energy of about 350 EeV is not ruled out.

To develop the points of comparison suggested by Figs. 2 and 4, in Fig. 5 we show the scatter plot for 50 showers of the shower maximum (X_{max}) versus the number of particles at maximum (N_{max}) for both the proton and neutrino primaries for several assumed values of the incident neutrino primary energy and the scale M. The proton shower energy is fixed at $E = 10^{20} eV$, while the initial neutrino energy is varied for each of the values M=2, 2.5 and 3 TeV chosen. We find that the neutrino showers show more scatter than do the proton showers. The scatter decreases as the value of M decreases i.e. as the $\sigma_{\nu p}$ *increases*. Although the mean values for these two types of showers differ for most of the parameter space there exist many neutrino generated individual showers which are very similar to the proton shower with $E = 100$ EeV. For $M = 2.0$ TeV we find that there is somewhat more scatter but the same average N_{max} and X_{max} values for neutrino showers with primary energy 125 EeV compared to proton showers with primary energy of 100 EeV. Almost the same statement applies to the comparison of neutrino showers where $M = 2.5$ TeV and $E = 150$ EeV are compared to the proton sample, though the X_{max} value is a bit higher in this case.

As mentioned above, the Fly's Eye and HiRes, using the air flourescence technique, are the only experiments that directly reconstruct the profiles. The others, the Volcano Ranch array, the Haverah Park array, the Sydney University array (SUGAR), the Yakutsk array and the Akeno Giant Air-Shower Array (AGASA) all employed particle detection schemes to observe the lateral pattern of the shower particles at ground level. For example, AGASA deduces the energy of the primary by measuring the density of charged particles at 600 m from the shower core. Averaging over 50 showers, we compare this fundamentally important, lateral distribution of charged

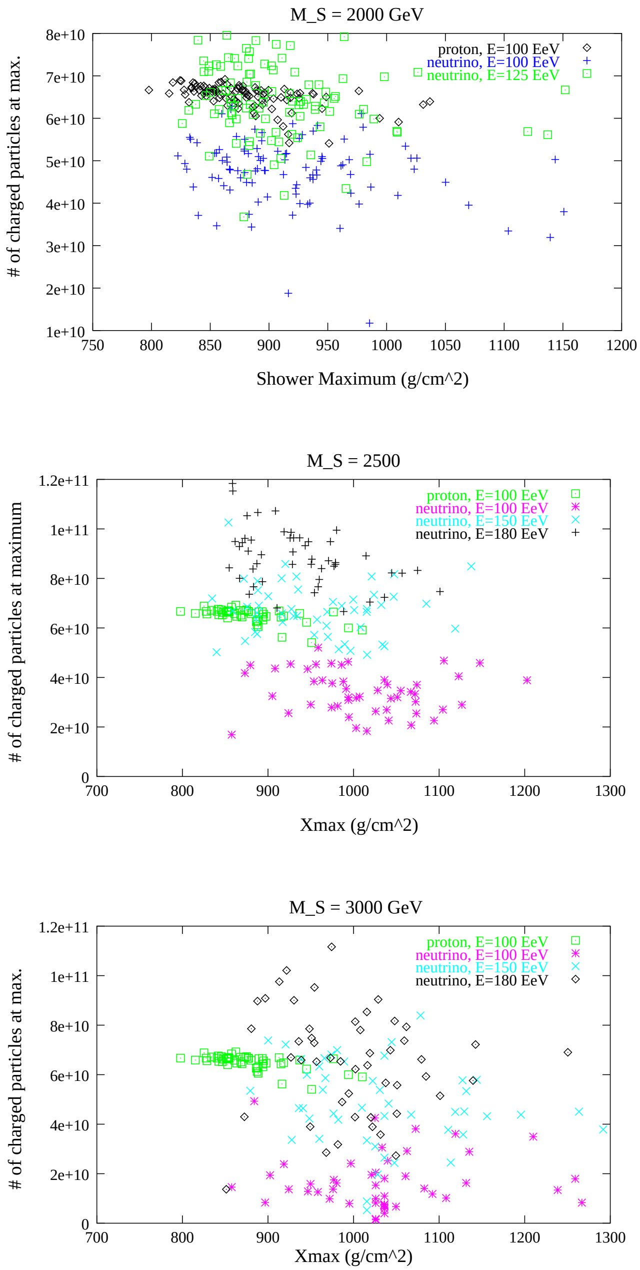

Figure 5: The number of charged particles at shower maximum (N_{max}) vs. the atmospheric depth of the maximum (X_{max}) for several different choices of the quantum gravity scale M and the incident neutrino energy. The result for proton ($E = 100$ EeV) induced showers within the standard model are shown for comparison. Fifty showers are shown in each case.

particles at ground level for the two types of showers in Fig. 6. We find that the two distributions are *very similar* for a number of neutrino shower M and E_ν choices and $E_p = 100$ EeV.

We next compare the total number of charged particles at ground level for the proton and neutrino generated air showers. The results are shown in the scatter plot, Fig. 7. We find that the total number of particles at ground level is in general smaller for a neutrino in comparison to a proton primary if both the incident particles have the same energy. This difference disappears if the $\sigma_{\nu p}$ is very large (equivalently M is small). For a given value of M, one can raise the neutrino energy and see the number of particles at ground level increase toward the value of the proton shower. For example, for $M = 2.0$ TeV we find that the average number of charged particles at ground level for neutrino showers is the same as for proton showers if the incident neutrino has a 25% higher energy. For larger values of M, of the order of 3.0 TeV, we find that the number of charged particles at ground level is again the same as that of a proton induced shower with primary energy 100 EeV, if the neutrino primary has energy roughly equal to 180 EeV. Based on this diagnostic alone, these results suggest that AGASA might interpret a shower generated by a neutrino primary to be that generated by a proton of a somewhat smaller energy.

The identity of the primary particle (p, Nucleus or γ) is deduced by AGASA on the basis of the muon content of the shower. The lateral dependence of the number of muons observed at ground level, again averaged over 50 showers, is shown in Fig. 8. We find that the muon distribution for the two types of primaries is approximately the same for a number of E_ν and M combinations. This diagnostic is evidently not a sensitive tool for discriminating between the proton-induced and neutrino-induced showers.

Coming back to the longitudinal development of the charged particles, we show a variety of cases, averaged over 50 showers, in Fig. 9. In this case we find significant difference between the showers generated by neutrino and proton primaries. The neutrino showers in general show maximum closer to the ground level. This difference, however, essentially disappears if the scale M is roughly 2 TeV. However, as one can see in these plots and in the scatter plots of N_{max} vs. X_{max}, Fig. 5, if M is a bit above 2.0 TeV at 2.5 or 3.0 TeV, then one cannot bring the average position of shower maximum, X_{max} into line with the average profile of proton showers of a given energy.[10] Since

[10]This insensitivity of the depth of shower maximum just reflects the weak $ln(E)$ de-

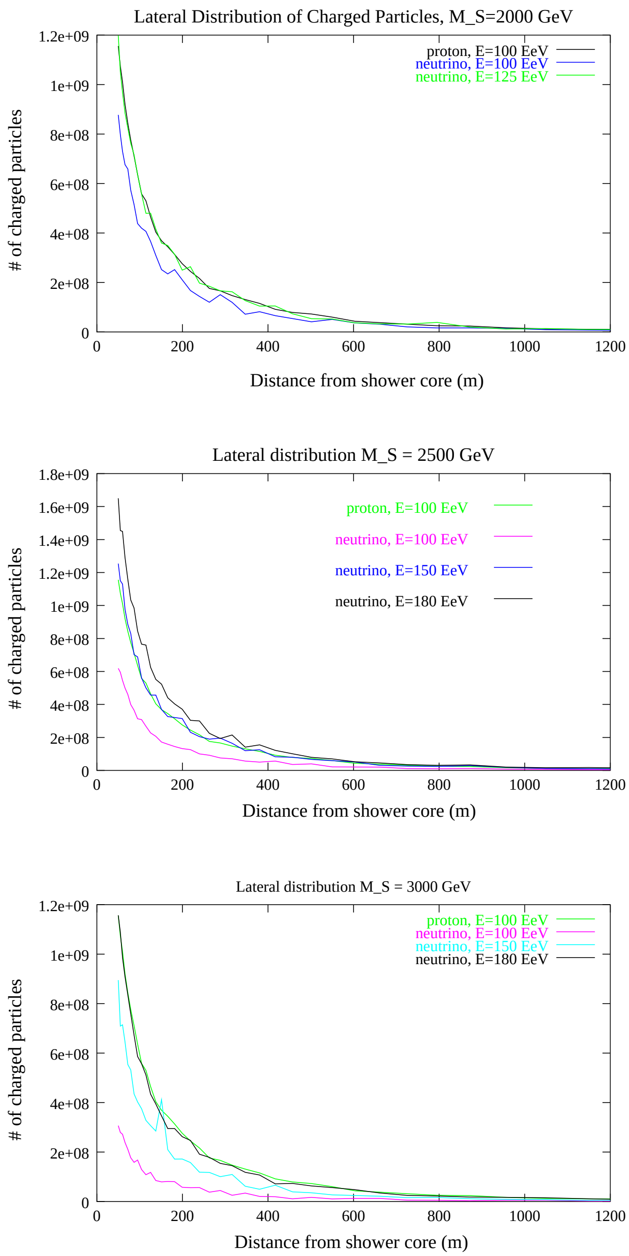

Figure 6: The lateral distributions of charged particles at ground level for several different choices of the quantum gravity scale M and the incident neutrino energy. The result for proton ($E = 100$ EeV) induced showers within the standard model are shown for comparison. Each curve is an average over 50 showers.

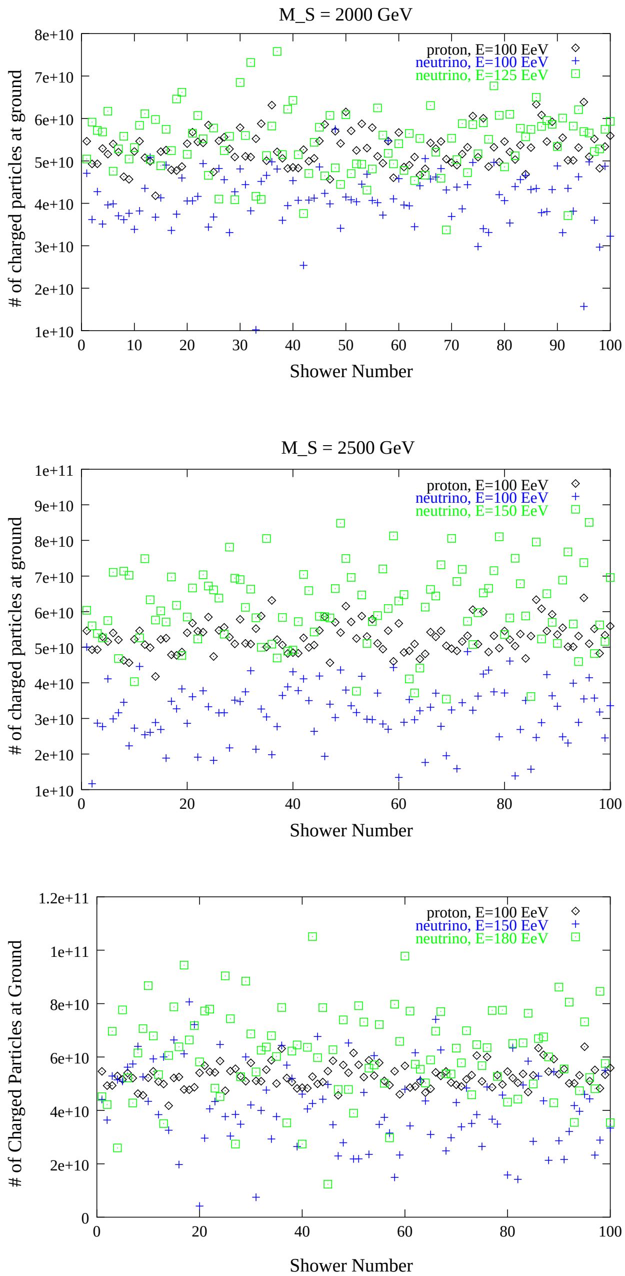

Figure 7: The number of charged particles at ground level for several different choices of the quantum gravity scale M and the incident neutrino energy. The result for proton ($E = 100$ EeV) induced showers within the standard model are shown for comparison.

shower-to- shower fluctuations are large, as seen in Figs. 2 and 4, it requires a significant sample such as the 50 - 100 shown in our study, to get good discrimination.

4 Discussion and Conclusions

The conjecture that UHE, super-GZK cosmic ray showers are caused by neutrinos with large UHE cross sections is almost as old as the field itself [19]. Revisiting this idea in a new theoretical framework [18], we proposed models that achieve interestingly large cross sections [17]. We speculated that the GZK "barrier" could be then broken by neutrinos. The next question to answer is whether the shower events predicted look like events observed. Or are the characteristics so different from observed showers, which are generally compared to those of the simulations of proton, nucleus and gamma initiated showers, that the neutrino can be eliminated as a candidate for the super GZK showers? *Our conclusion based on this study is no, they cannot be eliminated as candidates.* For a range of values of the fundamental scale M in the neighborhood of $2-3$ TeV, there are neutrino energies 25% - 75% above that of the comparison proton model where the simulations match quite closely. As noted in the introduction, the same analysis applies to a variety of cases - different interactions and different identities of primary particle. Given that the same cross section input is not unique to the low scale gravity inspiration used here, this result is of quite general use.

Whether neutrinos follow the standard model extrapolations [40, 41], are enhanced "modestly" by 3-5 orders of magnitude or "extravagantly" by more than 5 orders of magnitude, the search for UHE neutrino induced events at present and new facilities [42, 43] will be an exciting one.

Note Added: As we were completing this paper, a closely related work appeared [44]. The cross sections considered in their work are well below 10 mb, while we concentrate primarily on cross sections above this value. Where cross sections are roughly the same, results and conclusions qualitatively agree.

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pendence of the maximum [39].

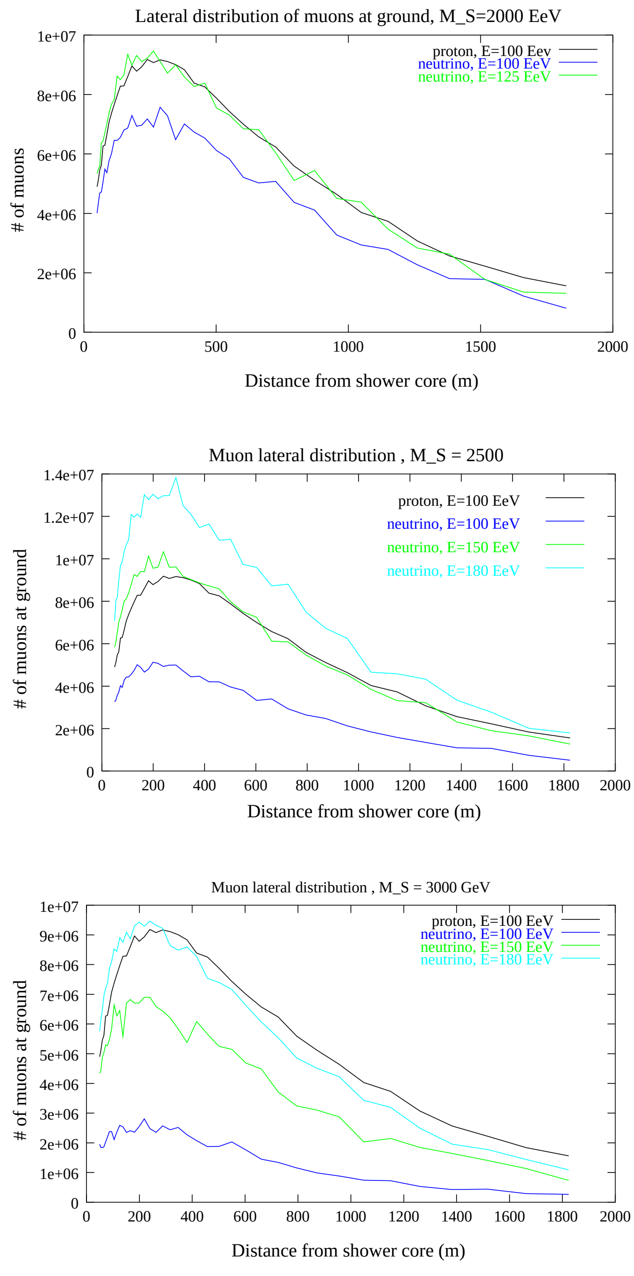

Figure 8: The lateral distribution of muons at ground level for several different choices of the quantum gravity scale M and the incident neutrino energy. The result for proton ($E = 100$ EeV) induced showers within the standard model are shown for comparison. The curves show averages over 50 showers.

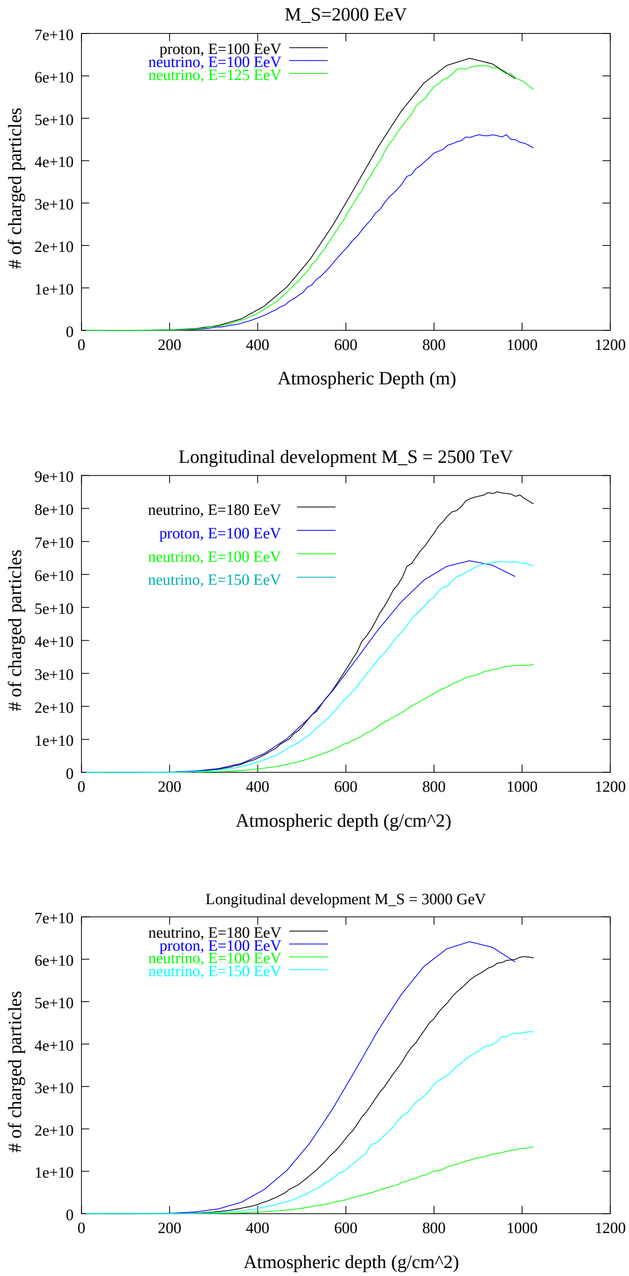

Figure 9: The longitudinal distribution of charged particles for several different choices of the quantum gravity scale M and the incident neutrino energy. The result for proton ($E = 100$ EeV) induced showers within the standard model are shown for comparison. Curves show averages over 50 showers.

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References

[1] M. Nagano and A. Watson, *Rev. Mod. Phys.* **72**, 689 (2000). This review includes a history of the field, a description of the experiments and a summary of the possible explanations.

[2] J. Ebert and P. Sommers, *Astrophys. J.* **441**, 151 (1995). These authors give a review of the possibilities for explaining the 320 EeV event observed by the Fly's Eye [38]. The list still covers all of the basic ideas.

[3] G. Sigl, astro-ph/0008364. This reference reviews some current developments in various standard ideas for explaining UHE cosmic rays.

[4] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, Sov. Phys. JETP Lett. **4**, 78 (1966).

[5] J. Puget, F.W. Stecker and J. Bredekamp, *Astrophys. J.* **205**, 638 (1976); F.W. Stecker and M.H. Salamon, *Astrophys. J.* **512**, 521 (1999); J. Wdowczyk, W. Tkaczyk and A. Wolfendale, *J. Phys. A* **5**, 1419 (1972).

[6] F. Aharonian, P. Bhattacharjee and D. Schramm, *Phys. Rev. D* **46**, 4188 (1992).

[7] J. MacGibbon and R. Brandenberger, *Phys. Rev. D* **47**, 2283 (1993).

[8] V. Berezinsky, *Phys. Rev. Lett.* **79**, 4302 (1997).

[9] V. Kuzmin and I. Tkachev, Phys. Rep. **320**, 199 (1999).

[10] D. Chung, G. Farrar and E. Kolb, *Phys. Rev. D* **57**, 4606 (1998).

[11] S. Raby, *Phys. Lett.* **B422**, 158 (1998).

[12] L. Clavelli, hep-ph/9908342.

[13] T. Kephart and T. Weiler, *Astropart. Phys.* **4**, 271 (1996).

[14] S. Wick, T. Kephart, T. Weiler and P. Biermann, astro-ph/0001233.

[15] L. Gonzalez-Mestres, in *Proceedings of the 25th International Cosmic Ray Conference*, 1997, Durban, edited by M. Potgieter, B. Raubenheimer and D. van der Walt (World Scientific, Singapore), Vol 6, p. 113.

[16] S. Coleman and S. Glashow, *Phys. Rev. D* **59**, 116008 (1999).

[17] P. Jain, D. McKay, S. Panda and J. Ralston, *Phys. Lett.* **B484**, 267 (2000).

[18] N. Arkadi-Hamed, S. Dimopolous and G. Dvali, *Phys. Lett.* **B429**, 263 (1998). Some precursors of the model are: V. Rubakov and M. Shaposhnikov, *Phys. Lett.* **B125**,136,(1983); B. Holdom, *Nucl. Phys.* **B233**, 413 (1983); M. Visser, *Phys. Lett.* **B159**, 22 (1985); E. Squires, *Phys. Lett.* **B167**, 286 (1986); J. Hughes, J. Liu and J. Polchinski, *Phys. Lett.* **B180**, 370 (1986); G. W. Gibbons, D. L. Wiltshire, *Nucl. Phys.* **B287**, 717 (1987); K. Akama, *Prog. Theor. Phys.* **78**, 184 (1987); A. Barnaveli and O. Kancheli, *Sov. J. Nucl. Phys.* **51**, 573 (1990); I. Antoniadis, it Phys. Lett. **B246**, 377 (1990) ; I. Antoniadis, C. Muñoz and M. Quiros, *Nucl. Phys.* **B397**, 515,(1993). I. Antoniadis, K. Benakli and M. Quiros, *Phys. Lett.* **B331**, 313 (1994). String realizations of the idea are presented in: I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phys. Lett.* **B463**, 257,(1998); G. Shiu and S.-H.H. Tye, *Phys. Rev. D* **58**, 106007 (1998). A different picture where effects of gravity can be strong at relatively low energies is presented in: L. Randall and R. Sundrum, *Phys. Rev. Lett.* **83**, 3370 (1999); *Phys. Rev. Lett.* **83**, 4690 (1999).

[19] Early versions of the idea of enhanced UHE neutrino-nucleon cross sections include V. Berezinsky and G. Zatsepin, *Phys. Lett. B* **28**, 423 (1969); G. Domokos and S. Nussinov, *Phys. Lett.* **B187**, 372 (1987); G. Domokos, B. Elliot, S. Kovesi-Domokos, and S. Mrenna, *Phys. Rev. Lett.* **63**, 844 (1989); J. Bordes, H.-M. Chan, J. Faridani, J. Pfaudler and S.-T. Tsou, *Astropar. Phys.* **8**, 135 (1998).

[20] G. Farrar and P. Biermann, *Phys. Rev. Lett.* **81**, 3579 (1998).

[21] G. Sigl, D. Torres, L. Anchordoqui and G. Romero, astro-ph/ 0008363.

[22] A. Virmani, S. Bhattacharya, P. Jain, S. Razzaque, J. Ralston and D. McKay, astro-ph/0010235.

[23] H. Goldberg and T. Weiler, *Phys. Rev. D* **59**, 113005 (1999). This reference gives a rather general and model independent treatment of the applications of dispersion relations and unitarity to the impact of high energy enhancements on low energy physics. Our models are comfortably within the bounds of this reference.

[24] S. Nussinov and R. Shrock, *Phys. Rev. D* **59**, 105002 (1999).

[25] M. Kachelrieß and M. Plümacher, *Phys. Rev. D* **62**, 103006 (20000).

[26] M. Bando, T. Kugo, T. Noguchi and K. Yoshioka, *Phys. Rev. Lett.* **83**, 3601 (1999); M. Bando and T. Noguchi hep-ph/0011374. The latter reference points out that incorporating chiral fermions in extra dimension models seems to require that the brane be treated as a rigid object, with no fluctuations. This is an open question at the moment.

[27] Besides the s^2 behaviour several slow-growth models are also studied in [17].

[28] G. Domokos and S. Kovesi-Domokos, *Phys. Rev. Lett.* **82**, 1366 (1999). This paper makes the point that hadronic size cross sections mean that neutrinos would be produced directly at the sources at energies and multiplicities comparable to hadrons. Proton energies several orders of magnitude higher than the neutrino energies are not necessary.

[29] S. Mrenna, *Phys. Rev. D* **45**, 2371 (1992). To our knowledge, this is the earliest Monte Carlo simulation comparing proton induced to new neutrino physics induced extensive air showers. The energies studied in this paper are in the PeV range.

[30] G. Domokos, S. Kovesi-Domokos and P. Mikulski, hep-ph/0006328, find conclusions similar to ours in a study of shower profiles in a one- dimensional shower model. Lateral distributions are not treated there, of course.

[31] T. Han, J.D. Lykken and R.-J. Zhang, *Phys. Rev. D* **59**, 105006 (1999); G.F. Giudice, R. Rattazzi and J.D. Wells, *Nucl. Phys.* **544**, 3 (1998); J. Hewett, *Phys. Rev. Lett* **82**, 4765 (1999).

[32] I. Antoniadis and K. Benakli in *Proceedings of the 7th International Symposium on Particles, Strings and Cosmolgy*, Lake Tahoe, 10-16 Dec. 1999 (World Scientific, Editors K. Cheung, J. Gunion and S. Mrenna).

[33] P. Nath, hep-ph/0011177.

[34] S. Cullen and M. Perlestein, *Phys. Rev. Lett.* **83**, 268 (1999). These authors calculate the SN1987a bounds on M, quoting n=2, 3, and 4 examples, with caveats. For recent reviews of the status of experimental bounds on extra dimension models see, G. Landsberg, hep-ex/0009038, To appear in Proc. XXXth International Conf. on High Energy Physics ICHEP 2000, Osaka, Japan; S. Raychaudhuri, Pramana **55**, 171 (2000); M. Peskin, hep-ph/0002041; I. Antoniadis and K. Benakli [32].

[35] R. Glauber, in *Lectures in Theoretical Physics*, edited by A.O. Barut and W.E. Brittin (Interscience, New York, 1959).

[36] J. Engel, T. Glaisser, P. Lipari and T. Stanev, *Phys. Rev. D* **46**, 5013 (1992).

[37] C. Tyler, A. Olinto and G. Sigl, *Phys. Rev. D* **63**, 055001 (2001).

[38] D. Bird et al., *Astrophys. J.* **441**, 144 (1995).

[39] B. Rossi, *High Energy Particles* (Prentice-Hall, New York, 1952).

[40] Yu. Andreev, V. Berezinsky and A. Smirnov, *Phys. Lett.* **B84**, 247 (1979); D. W. McKay and J. P. Ralston, *Phys. Lett.* **B167** 103 ,1986. M. H. Reno and C. Quigg, *Phys. Rev. D* **37**, 657 (1988).

[41] G. M. Frichter, D. W. McKay and J. P. Ralston, *Phys. Rev. Lett.* **74**, 1508-1511 (1995); J. P. Ralston, D. W. McKay, and G. M. Frichter, in *International Workshop on Neutrino Telescopes*, (Venice, Italy, 1996), edited by M. Baldo-Ceolin; astro-ph/9606007; ; R. Gandhi, C. Quigg, M. H. Reno, I. Sarcevic, *Astropart. Phys.* **5**, 81 (1996); R. Gandhi, C. Quigg, M. H. Reno, I. Sarcevic, *Phys. Rev. D* **58** (1998) 093009.

[42] D. Zavrtanik, *Nucl. Phys. Proc. Suppl.* **B85**, 324 (2000).

[43] For an overview of the proposed IceCube, see *The IceCube NSF proposal at http://pheno.physics.wisc.edu/icecube/*

[44] L. Anchordoqui, H. Goldberg, T. McKauley, T. Paul, S. Reucroft and J. Swain, hep-ph/0011097.